17th International Conference on Environmental Science and Technology

Athens, Greece, 1 to 4 September 2021

Validation of ENVI-met microscale model with in-situ measurements in warm thermal conditions across Athens area

KOLETSIS I.[1,2], TSELIOU A.[1,3], LYKOUDIS S.[4], TSIROS I.X.[1], LAGOUVARDOS K.[2], PSILOGLOU B.[2], FOUNDA D.[2] and PANTAVOU K.[1]*

[1] Laboratory of General and Agricultural Meteorology, Department of Crop Sciences, Agricultural University of Athens, Iera Odos St. 75, 11855, Athens, Greece

[2]National Observatory of Athens, Institute for Environmental Research and Sustainable Development, Palaia Penteli, 15236, Athens, Greece

[3]College of Natural and Health Sciences, Zayed University, P.O. Box 19282, Dubai, United Arab Emirates

[4]Independent Researcher, Akrita 66, 24132, Kalamata, Greece

*corresponding author: Katerina Pantavou
e-mail:kpantavou@aua.gr

Abstract Validation is critical for quantifying accuracy, errors and limitations of models' results. This study examines the ability of ENVI-met model to simulate thermal conditions in high spatial resolution. Field measurements from 11 central sites (squares and parks) across the greater area of Athens, Greece, incorporating 15 days of campaigns in July and August were used. Air temperature, relative humidity, wind speed, grey globe temperature and total solar radiation were monitored at 1.1 m above the ground using a mobile meteorological station. In addition, Mean Radiant Temperature, Physiologically Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) were calculated incorporating in-situ measurements. The full force method for ENVI-met initial conditions was applied, using hourly data from the nearest meteorological stations. Validation metrics including Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and the index of agreement (d) were used to measure the model accuracy. The results showed that air temperature is simulated with adequate accuracy (MAE = 1.6 °C and d = 0.8) while PET and UTCI also present a high percentage of agreement (MAE = 5.3 °C and 3.3 °C; d = 0.7 and 0.8, respectively). Overall, the study provides further confidence that the ENVI-met can be utilized as a reliable model for further research analysis.

Keywords: ENVI-met; thermal indices; field surveys; micrometeorological measurements; summer

1. Introduction

The rapid increase of urbanization worldwide affects the living environment within cities. The heat island effect leads to an increase in the air temperature inducing unfavorable thermal conditions (Buchin et al. 2016; Salata et al. 2016). Modeling techniques have become a powerful tool to investigate the thermal environments especially during the summer season, when the thermal conditions over cities are deteriorated. A large number of studies focus on thermal conditions across urban Mediterranean areas examining possible interventions to ameliorate thermally uncomfortable conditions using ENVI-met model (Tsoka et al. 2017; Chatzinikolaou et al. 2018). ENVI-met is the most commonly used software when addressing the impact of urban design on environmental variables and microclimate. It is a three-dimensional microclimate model, based on fundamental laws of fluid dynamics and thermodynamics and designed to simulate complex surface-vegetation-air interactions in the urban environment (Bruse and Fleer, 1998).

Model accuracy is of high importance to generate a useful output. In this study, the latest version of ENVI-met (2020) and the full forced method are applied to take advantage of the maximum model capabilities in order to achieve the best prediction accuracy. The accuracy of high-resolution simulations of 15 days during summer season in Athens, Greece is validated using data collected on-site during field measurements.

2. Data and Model Set up

ENVI-met model was used to simulate the micrometeorological and the thermal conditions in 11 central sites across the greater area of Athens, Greece (Fig. 1).

ENVI-met simulations were performed using geospatial data provided by the Hellenic Cadastre for buildings' dimensions and information collected by on-site visits for vegetation, trees and soil type. The model geometry and the characteristics of 3D plants and soil types for the 11 simulated domains are presented in Table 1.

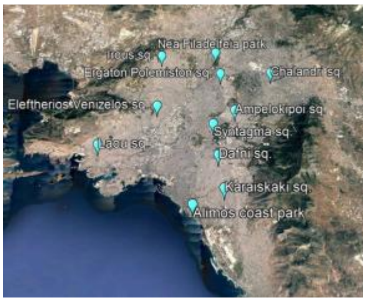

Figure 1. The 11 central sites across the greater Athens area used for model simulations.

Table 1. The model geometry, the number of different soil profiles and 3D plants of the study areas.

	Site	Model Geometry			
		Domain Size (grids)	Core XY domain (m)	# Soil Profiles	# 3D Plants
1	Karaiskaki sq.	180 x 180 x 30	270 x 270	7	254
2	Alimos coast park	180 x 180 x 30	270 x 270	9	140
3	Syntagma sq.	190 x 190 x 30	285 x 285	7	161
4	Erg. Polemistonsq.	227 x 200 x 45	340.50 x 300	8	420
5	Nea Filadelfia park	169 x 176 x 30	253.50 x 264	4	164
6	Irous sq.	214 x 163 x 45	321 x 244.50	8	140
7	Ampelokipoi sq.	190 x 190 x 70	285 x 285	8	290
8	Chalandri sq.	210 x 187 x 60	315 x 280.50	8	134
9	Dafni sq.	240 x 227 x 60	360 x 340.50	5	81
10	El. Venizelos sq	170 x 170 x 60	255 x 255	5	90
11	Laou sq.	190 x 190 x 60	285 x 285	4	196

All model domains have fine horizontal grid resolution of 1.5 x 1.5 m while the grid sizes in the vertical axis vary. The base vertical grid analysis is 2 m, however the lowest grid box is splitted into 5 subcells in order to approach better the height of the in-situ measurements used for model validation. As initial conditions we used data of air temperature (Tair in °C), relative humidity (RH in %), wind speed (WS in m/s) and direction (WD in degrees), precipitation (R in mm) and atmospheric pressure (P in hPa) derived by the National Observatory of Athens (NOA), the Hellenic National Meteorological Service (HNMS) and the automatic weather stations network (NOAAN) of NOA (Lagouvardos et al. 2017). Also, for the full forcing, we used total solar radiation (SR in W/m^2) and longwave radiation (LR in W/m^2), from the actinomertic stations of NOA at Penteli and Thissio, the only sites routinely measuring these parameters in the greater Athens area. The beginning of the simulation time was set up from midnight and before the sunrise ensuring stable conditions (Schinzato et al. 2019). In order to avoid any model spin up effects, the first 8-10 hours of the model run were discarded. This approach significantly increases the model run time, but improves model's performance (Middel et al. 2014). Thermal conditions were estimated using Physiologically Equivalent Temperature (PET in °C) and Universal Thermal Climate Index (UTCI in °C) with the BioMET add-on software package of ENVI-met.

ENVI-met results were validated by in-situ micrometeorological measurements. Fifteen days of campaigns in July and August was carried out in the 11 locations across the metropolitan area of Athens, Greece. A mobile weather station was used to monitor Tair, RH, WS, and grey globe temperature (Tgl in °C) at the height of 1.1 m. Mean radiant temperature (Tmrt in °C) was calculated using Tair, Tgl, and WS (ISO 7726, 2001) and the PET, UTCI indices using the Rayman software (Matzarakis et al. 2007, 2010).

The accuracy of ENVI-met simulations was quantitatively examined using the following metrics: *(a)* Root Mean Square Error (RMSE), *(b)* Mean Absolute Error (MAE), and *(c)* index of agreement (d) (Willmott 1982, Yang et al. 2013, Lee et al. 2016, Acero and Arrizabalaga 2018, Liu et al. 2018). A value of 1 for d corresponds to a perfect match, and 0 indicates no agreement at all (Willmott, 1981). The accuracy of PET and UTCI classifications of thermal sensation was examined using the percent of correct predictions and the Goodman and Kruskal's gamma measure of rank correlation.

3. Results

3.1 Qualitative comparison

ENVI-met simulations of Tair, RH, WS and Tmrt at the height of 1.4 m were compared to those recorded on-site during the field measurements campaign. The Tair simulations were in a very good agreement with the measured Tair in all model runs (Fig. 2a). The Tair measurements ranged between 22.6 °C and 40.4 °C and the simulated Tair ranged between 26.2 °C and 38 °C; while their maximum difference was calculated at 4.7 °C.

On the contrary, ENVI-met overestimated RH (Fig.2b) differing by ~35% from the field measurements. Nevertheless, ENVI-met seems to reproduce successfully RH variation over time attributing the time frames at which the extreme RH values are taken place in accordance with the in-situ measurements. The RH overestimation is opposed to the findings of previous studies in which an overestimation of Tair and an underestimation of air humidity were reported (Yang et al. 2013, Lee et al. 2016).

The simulated Tmrt was also overestimated compared to the Tmrt calculated from the field data producing the highest deviations on the maximum values (Fig.2c). The simulated WS showed significant differences compared to the measurements especially for some of its maximum values in which a clear overestimation was evident (Fig. 2d). This discrepancy may be due to the neighboring obstacles and the local wind channeling, where the model seems to intensify. Moreover, another factor may be the obstruction of the wind field and its modification by passengers or by people taking part in the campaigns giving lower observed wind speed values.

Finally, the comparison of in-situ and simulated data showed that the model provided quite good results for the thermal indices of PET and UTCI as presented in Figures 2e and 2f, respectively. A slightly overestimation is evident. The number of UTCI data is smaller due to the limitations of its calculation (Matzarakis et al. 2007, 2010).

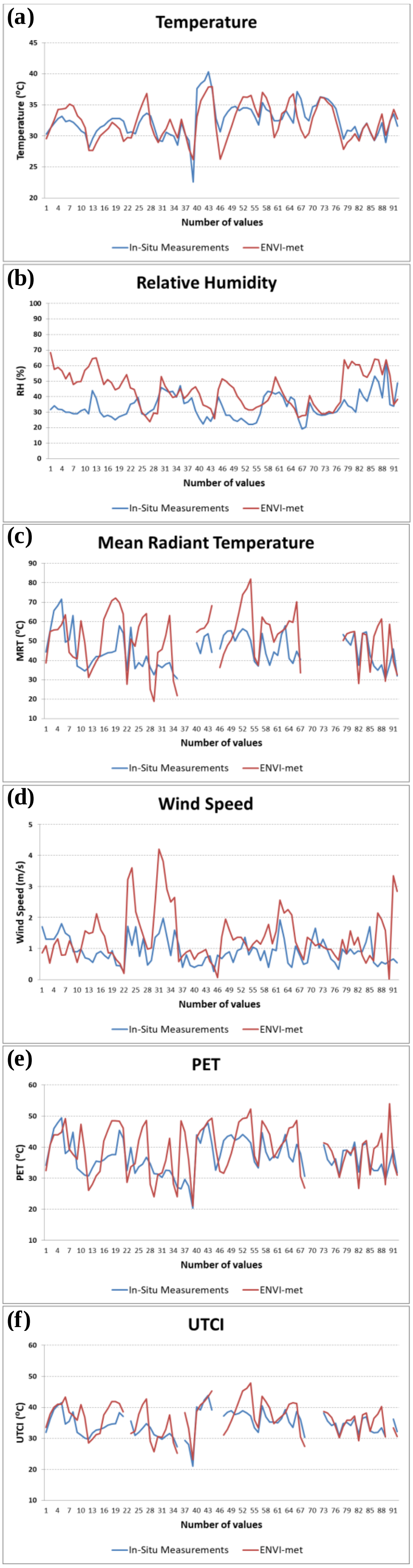

Figure 2. ENVI-met simulations and field measurements of (a) air temperature, (b) relative humidity, (c) mean radiant temperature, (d) wind speed, (e) PET and (f) UTCI.

3.2 Quantitative comparison

The results of the statistical metrics throughout the 15 days campaign for all simulations are presented in Table 2. The agreement between Tair measurements and simulations was high. The value of d (0.8) indicates that ENVI-met captures the Tair measurement trend well, while the RMSE and MAE metrics were evaluated as very good, with values 2.0 ^{0}C and 1.6 ^{0}C, respectively.

The RMSE and MAE of RH were high indicating possible errors at ENVI-met simulations (Table 2). These could be due to the failure of ENVI-met to simulate successfully the solar radiation (Liu et al. 2018) and/or the moisture brought by the wind.

Table 2. Validation of ENVI-met performance (RMSE, MAE, d) for the 15 days summer season simulations runs.

	RMSE	MAE	d
Tair (°C)	2.0	1.6	0.8
RH (%)	15.1	12.0	0.5
Tmrt (°C)	13.8	11.1	0.6
WS (m/s)	0.9	0.6	0.5
PET (°C)	6.9	5.3	0.7
UTCI (°C)	4.3	3.3	0.8
PET thermal class	1.0	0.7	0.7
UTCI thermal class	0.8	0.6	1.0

The simulated Tmrt also presents significant differences compared to the Tmrt estimated from the measurements. The RMSE and MAE values were 13.8 °C and 11.1 °C respectively, while the index d value was 0.6.

The MAE of WS was 0.6 m/s and the RMSE was 0.9 m/s (Table 2). The index d was low (d=0.5) indicating significant differences between ENVI-met simulations and the measurements. This discrepancy might be caused by the fact that the ENVI-met cannot incorporate real-time wind speed and direction.

PET and UTCI values were adequately simulated by ENVI-met according to the index of agreement, taking values of d = 0.7 and d = 0.8, respectively. The values of RMSE were 6.9 °C for PET and 4.3 °C for UTCI and of MAE were 5.3 °C for PET and 3.3 °C for UTCI. Given that the aim of this project is to evaluate the model accuracy in simulating thermal sensation, the PET and UTCI classifications according to their assessment scales (Matzarakis and Mayer, 1977; Pantavou 2014) were also considered. The index of agreement (d) took values of 0.7 for PET simulated classifications of thermal sensation and 1.0 for UTCI. The percentage of correct simulations for PET was 48.9% and for UTCI 48.2% while Gamma statistic was estimated to 0.62 and 0.76, respectively, suggesting that ENVI-met captures adequately the thermal sensation.

4. Conclusions

The results reveal that ENVI-met full forcing option replicates quite accurately the micrometeorological and thermal conditions in open urban places in Athens, Greece. The most successfully simulated variable holding the highest validation scores was the air temperature - an important meteorological parameter affecting people's thermal perception (Salata et al. 2016). Low validation scores were produced for the relative humidity; however it should be noticed that people's perception with respect to air humidity is ambiguous, thus it is expected to have a small effect on people's thermal perception. Overall, we conclude that ENVI-met model can be utilized as a reliable tool for research analysis of thermal conditions in open urban places.

Acknowledgements

The authors would like to acknowledge the Institute for Environmental Research and Sustainable Development of the National Observatory of Athens and the Hellenic National Meteorological Service for providing meteorological data. This project has received funding from the Hellenic Foundation for Research and Innovation (HFRI) and the General Secretariat for Research and Technology (GSRT), under grant agreement No 146.

References

Acero, A.J., Arrizabalaga J. (2018), Evaluating the performance of ENVI-met model in diurnal cycles for different meteorological conditions, Theor. Appl. Climatol., 131, 455–469.

Bruse M. and Fleer H. (1998), Simulating surface-plant-air interactions inside urban environments with a three-dimensional numerical model, Environ. Model. Softw., 13, 373–384.

Buchin, O., Hoelscher, M.-T., Meier, F., Nehls, T., Ziegler, F. (2016), Evaluation of the health-risk reduction potential of countermeasures to urban heat islands. Energy and Buildings, 114, 27–37.

Chatzinikolaou E., Chalkias C., Dimopoulou E. (2018), Urban Microclimate improvement using Envi-met Climate Model. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-4.

ENVI-met, version 4.2.2. (2020), A holistic microclimate model. https://envi-met.info/doku.php?id=files:downloadv4 (accessed April 9, 2021).

ISO 7726 (2001), Ergonomics of the thermal environment-Instruments for measuring physical quantities, International Organization for Standardization, Geneva.

Lagouvardos K., Kotroni V., Bezes A., Koletsis I., Kopania T., Lykoudis S., Mazarakis S., Papagiannaki N, Vougioukas K. (2017), The Automatic Weather Stations NOANN Network of the National Observatory of Athens: Operation and database, Geosci. Data J., 4, 4–16.

Lee, H.; Mayer, H.; Chen, L. (2016), Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, southwest Germany. Landsc. Urban Plan., 148, 37–50.

Liu Z., Zheng S., Zhao L. (2018), Evaluation of the ENVI-Met Vegetation Model of Four Common Tree Species in a Subtropical Hot-Humid Area, Atmosphere (Basel), 9, 198.

Matzarakis A., Rutz F., Mayer H., (2010), Modelling radiation fluxes in simple and complex environments: basics of the RayMan model, Int. J. Biometeorol., 54, 131–139. http://link.springer.com/10.1007/s00484-009-0261-0 (accessed October 18, 2019).

Matzarakis, A., Rutz, F., & Mayer, H. (2007), Modelling radiation fluxes in simple and complex environments—application of the RayMan model. Int. J. Biometeorol., 51, 323–334.

Matzarakis A and Mayer H (1997), Heat stress in Greece. *Int. J. Biometeorol.*, **41**, 34–39.

Middel A., K. Häb, A.J. Brazel, C.A. Martin, S. Guhathakurta, (2014), Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones, Landsc. Urban Plan. 122 16–28.

Pantavou K (2014), Biometeorological study in an urban Mediterranean climate: contribution to the evaluation of thermal sensation. Dissertation, National and Kapodistrian University of Athens, Athens, Greece.

Salata F., I. Golasi, R. Vollaro, A. Vollaro (2016), Urban microclimate and outdoor thermal comfort. A proper procedure to fit ENVI-met simulation outputs to experimental data. Sustain. Cities Soc., 26, 318-343.

Shinzato P., H. Simon, D.H. Silva Duarte, M. Bruse, (2019), Calibration process and parametrization of tropical plants using ENVI-met V4–Sao Paulo case study, Archit. Sci. Rev., 62, 112–125.

Tsoka S., Tsikaloudaki K., Theodosiou T. (2017), Urban space's morphology and microclimatic analysis: A study for a typical urban district in the Mediterranean city of Thessaloniki, Greece. Energy and Buildings, 156, 96-108.

Willmott, C.J. (1981), On the validation of models. Phys. Geog., 2, 184-194.

Willmott, C.J. (1982), Some comments on the evaluation of model performance., Bull. - Am. Meteorol. Soc. 63, 1309–1313.

Yang, X.; Zhao, L.; Bruse, M.; Meng, Q. (2013), Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces. Build. Environ., 60, 93–104.